Standing and Walking while using a Walker-like Exoskeleton

THESIS

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Abstract

Assistive devices that reduce the metabolic energy cost of walking will help humans with movement disorders or other mobility losses walk with less effort, and potentially increase their mobility and help with rehabilitation. Zimmerman (2016) designed a passive and powered cart-like walker exoskeleton that has the potential to reduce the metabolic energy cost of walking and increase stability. Our original goal was to improve the powered version of the cart and examine the speed and metabolic cost benefits of the powered version during overground walking and treadmill walking. Instead, here, we examine the stability during quiet standing of human subjects while standing with the passive version of the cart. Quiet standing stability is usually examined using the net center of pressure at the feet, examining its variability. Here, we analyze the individual limb centers of mass and the individual limb ground reaction forces to characterize standing stability. We find that in most conditions: (1) There is a positive correlation between the left and right components of center of pressure in the anterior-posterior direction, (2) a positive correlation between the left and right foot ground reaction forces in the medial-lateral and anterior-posterior direction. (3) The left and right foot medial-lateral center of pressure displacements are negatively correlated. (4) The correlation between medial-lateral and anterior-posterior center of pressure displacement is negative for the left foot and positive for the right foot. (5) The combined center of pressure displacement in the medial-lateral and anterior-posterior direction is positively correlated. (6) There are no observable differences between the Hands Off and Hands On centers of pressure and ground reaction forces. In future work, we seek to improve both analytic techniques to process the data as well as perform experiments with the powered version of the cart.

Acknowledgments

I would like to thank all of my mentors throughout my academic career, but especially my advisor Dr. Manoj Srinivasan. He has supported me throughout the research process and always encouraged curiosity throughout the way. I have learned a great deal from Manoj about not only the way people move, but how ‘we’ as researchers may “move” others. I am truly grateful for the opportunity to work with someone as well-versed and knowledgeable in all themes of life, thank you Manoj.

I would next like to thank Dr. Meera Menon for her guidance and compassion throughout my undergraduate career. Meera, without you I am not sure where I would be. You gave me the confidence needed to graduate academically, as well as in life. I am thankful to know and to have worked with you.

Lastly, I would like to thank my friends and family for cheering me on throughout the process of writing my thesis. It is in the most frustrating and deflating parts of my academic career where I am reminded of all of your kind words. Thank you.

Vita

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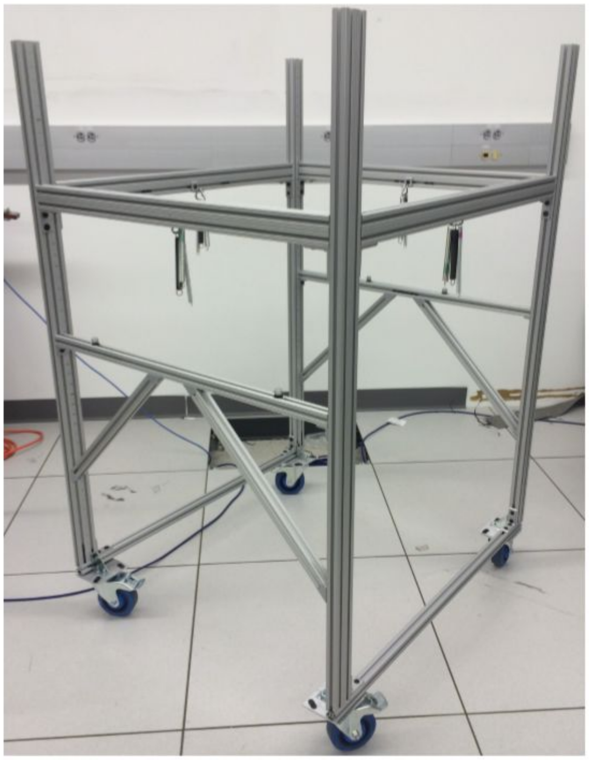
List of Abbreviations

Term	Definition
AP	Anterior-Posterior
ML	Medial-Lateral
CoP	Center of Pressure
GRF	Ground Reaction Force

CHAPTER 1: Introduction

1.1 *Motivation*

Movement disorders due to chronic conditions, acute injuries, or old age can reduce humans' ability to walk, making walking more effortful and less stable (Shahzad, 2016, Dietz and Sinkjaer, 2007, Pearson, 2004). Assistive devices, especially with an external source of power, can potentially reduce the effort required for walking, specifically, reducing the metabolic energy cost of walking (Lenzi, 2012, Vashista, 2016). Some complex exoskeleton devices have so far managed to reduce the energy cost of walking (Collins et al., 2015, Walsh, 2006). Zimmerman (Zimmerman, 2016) conceived and created a cart-like or a walker-like exoskeleton, perhaps the simplest possible exoskeleton devices (Figures 1.1-1.2). Our goal in this thesis was to build upon Zimmerman's work, both improving Zimmerman's device and examining the capabilities of such devices in improving stability and decreasing metabolic cost.



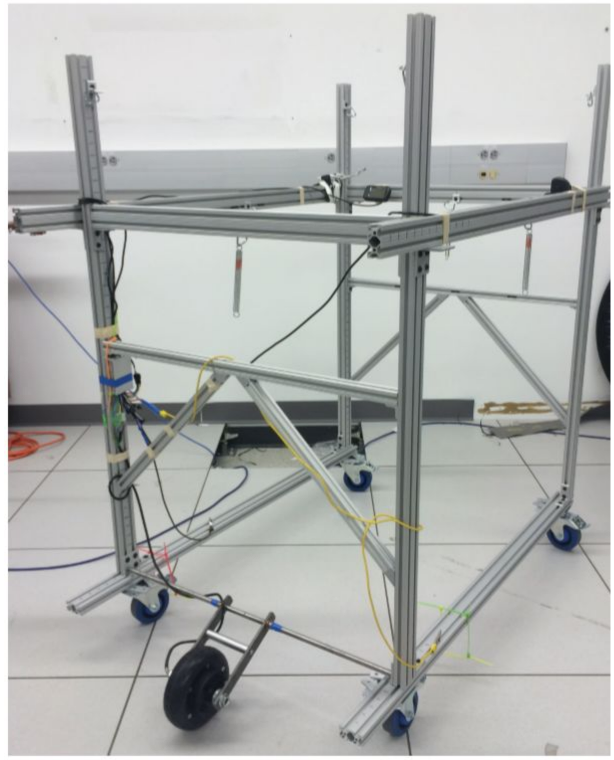


Fig .1.1. Passive walker-like exoskeletons from Zimmerman (2016).

Fig. 1.2. Active Version of Zimmerman's Walker-Like Exoskeleton. (Zimmerman, 2016).

Robotic devices that are seen in the field of physical therapy and task assistance today are often complex, which makes modeling the human biomechanics and human-device interactions difficult (Zimmerman, 2016). Simple models can be applied to these complex systems. However, the realized metabolic cost reduction often falls short of what is predicted by these simple models (Handford and Srinivasan, 2016) Hence, a simple exoskeleton mechanism would be useful to reduce the complexity of the device kinematics and improve the accuracy of the simple models. This simplicity may help us better understand the fundamentals of human-exoskeleton interaction in a dynamically simple context.

1.2 *Literature Review on Exoskeletons and Assistive Devices*

Ferris et al. (2007) attempt to provide recommendations for improving future exoskeleton designs by combining the field experience of engineers and physiologists (Ferris et al, 2007). They propose that a physiological lens be applied to two main goals of exoskeleton research: the reduction of metabolic cost of locomotion and minimizing the power required for actuating the exoskeleton (Ferris et al, 2007). Additional questions of interest are: (i) How long does it take the user to learn how to walk with the exoskeleton?, (ii) How does the exoskeleton affect the metabolic cost of walking for its user?, and (iii) How agile and stable is the user's movement while using the exoskeleton? (Ferris, 2007). Understanding how humans adapt to an exoskeleton is critical to designing an effective assistive device for walking, but the process is exoskeleton-dependent making it difficult to have a generalized understanding of how humans adapt to all types of exoskeletons (Ferris, 2007).

Lenzi studies the specific goal of reducing the muscle effort of walking through the use of powered exoskeletons, as muscle force is the main contributor to metabolic cost of walking (Lenzi, 2012). From this research it was observed that the assistive forces provided by the exoskeleton was able to reduce the muscle activation of the Gastrocnemius Medialis for all subjects and the Rectus Femoris for 2 subjects when compared to trials where the subjects walk unencumbered (Lenzi, 2012). Walsh et al (2006) used biomimetic design of an under-actuated leg exoskeleton to study how subjects walked with a 75lb payload with and without the exoskeleton. Through the collected kinetic and metabolic data it was found that the exoskeleton transfers loads to the ground with 90% and higher load transfer depending on the phase of gait (Walsh, 2006). This substantiates the potential advantage of using an exoskeleton to increase load carrying capacity and/or improve metabolic efficacy of walking. In another study done by Collins et al. (2015), it was found that the metabolic cost of human walking can be reduced by the use of an unpowered ankle exoskeleton. The results showed a 7.2 ± 2.6% decrease in metabolic cost of walking for healthy subjects under normal conditions (Collins et al., 2015). In a study on subjects recovering from a stroke, the effect of balance support on metabolic efficacy during walking was analyzed. A 16.2% (p-value$<$0.001) reduction in metabolic energy cost of walking was found in supported walking versus walking freely (Ijmker et al, 2013). Thus by improving or assisting balance control during rehabilitation there is a potential for the metabolic effort for balance control and walking to be reduced (Ijmker et al, 2013).

One open problem in exoskeleton research is to produce a device that improves both metabolic economy and stability. One challenge in realising this goal is that while there is an objective way to measure the metabolic cost during a task, stability is less well quantified (there are many competing notions of stability and robustness). Winter provides some methods for studying walking and standing using an inverted pendulum model (Winter, 1995). During standing, the difference between a subject's center of pressure and their center of mass is proportional to the horizontal acceleration of the center of mass (Winter, 1995). In other words, the difference between the center of pressure and center of mass appears to be the error signal for a subject's control system. In one recent study by Stodolka et al. , the characteristics of the center of pressure trajectory during quiet standing was explored. Unlike most studies on quiet standing, they considered the interplay between the action of the two feet (most prior studies lump the two feet into a single source of force). In 82% of subjects, the center of pressure displacement followed an anterior-posterior trajectory with a medial slant for the left foot and a lateral slant for the right foot center of pressure trajectory (Stodolka, 2020). Our analysis of standing stability in this thesis is similar in that we aim to treat the two feet as distinct actuators and examine how they contribute to standing stability.

1.3 *Description of Zimmerman's Research*

Zimmerman's (Zimmerman, 2016) cart-like assistive walker was designed with soft springs that connected the user to the cart (Fig. 1.1) The simple design of the device allowed for better modeling of the data collected. Through Zimmerman's testing, it was determined that there was around a 9% reduction in metabolic cost (p-value=0.0015) when going from normal walking to using a "simulated" active cart going at a constant speed (Zimmerman, 2016). A mathematical model was also developed from her research which confirmed the reduction in metabolic cost when using an active cart.

In Zimmerman's final iteration of the active assistive walker, a hub motor was attached to the frame of the cart to provide further propulsion to the user (Fig. 2.2) Zimmerman performed preliminary trials with one subject using the motorized active walker on the treadmill and the subject reported feeling a substantial forward force. This indicates that there is potential for metabolic reduction by using the motorized active walker. However, no complete metabolic or mechanical testing has been performed with this device, so the question of how much this device reduces the metabolic cost still remains. The initial purpose of our proposed research for this thesis was to perform the first rigorous testing of the motorized active cart prototype to investigate its effect of energy cost and provide further insight into how assistive walking devices can be improved to better help their users. This was not possible because of limited lab access due to the COVID-19 pandemic.

In addition to reducing walking effort, the device can potentially improve walking stability due to its broad base. Such improvements in stability may be desirable for an assistive walker. Here, we propose an analysis of the stability of Zimmerman's passive cart-like exoskeleton using data available from her research.

1.4.1 *Original Goals of Research*

The original objectives of this research were as follows:

• Modify and improve Zimmerman's active walker prototype so that the motor assistance can be controlled remotely by the researcher, so that the assistance can be controlled by the user adaptively, or the assistance controlled via based on the user behavior measured via some sensors.

• Perform treadmill trials with human subjects walking with the motorized active walker prototype.

• Analyze the data collected from tests and refine the current mathematical model.

• Test hypothesis of metabolic reduction and find optimal cart throttle setting for metabolic reduction.

• Capture the human-device interactions by measuring the forces exerted on the human.

1.4.2 *Revised Goals of Research*

Due to lab access restrictions because of COVID-19, the goals of this research needed to be reassessed to reflect the current capabilities. The revised goals of this research are to analyze how Zimmerman's passive cart-like walker contributes to stability while standing. This includes:

- Process ground reaction forces and motion data collected from Zimmerman's passive walker-like exoskeleton

- Analyze stability of the cart using computational methods including:

    - analyses of the ground reaction forces and center of pressure for the left and right foot individually as well as a combined quantity;

- an analysis of the ground reaction forces and center of pressure displacement in both the medial-lateral and anterior-posterior direction;
- correlation coefficient calculations between the left and right foot and between the medial-lateral and anterior-posterior components for a subject's center of pressure and ground reaction forces.

1.5 *Structure of Thesis*

In the next chapter (Chapter 2), the methods and results from research conducted by Sloan Zimmerman will be discussed. Additionally, progress made toward the original goals of research will be shown. Chapter 3 will show the results of our stability analysis of the person while standing with Zimmerman's passive cart-like walker, focusing on the center of pressure and the horizontal ground reaction forces. Chapter 4 will discuss the findings from the results as well as its implications for future research. Chapter 5 will summarize the findings of this paper and propose steps for future work.

CHAPTER 2: Methods

2.1 *Zimmerman's Research Methods and Description of Data Produced*

Two types of human subject trials were performed by Zimmerman, one with quiet standing and one with the user walking. For quiet standing, trials were performed with the user on the standalone force plates.

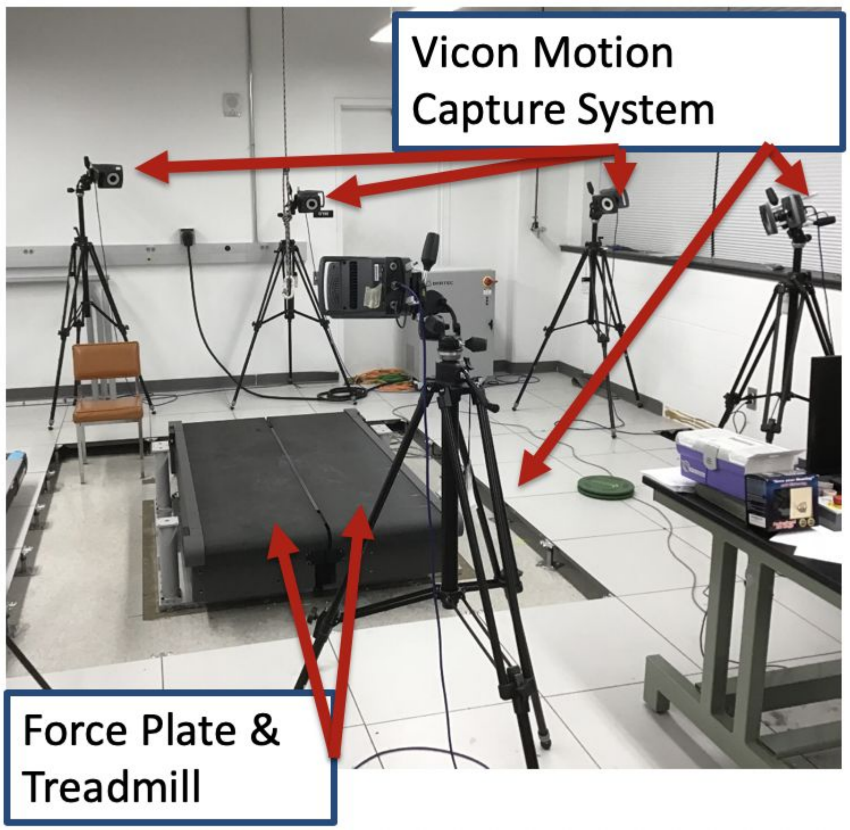


Fig. 2.1. Movement Laboratory Setup: Includes Bertec split-belt treadmill and Vicon Motion Capture System. Standalone Bertec force plates that the standing trials used are not shown here. Image courtesy Shepherd, 2018.

Ground reaction force measurements were taken in both types of trials via the Vicon data acquisition system. In addition, motion data was also captured in the treadmill trial via the Vicon Motion Capture system (Fig. 2.1). In trials where the user is walking, the treadmill was used exclusively and both force and motion data was collected.

For each of the trials described above there were two different test conditions; one with the user holding onto the cart and one where the user is not. For the remainder of this thesis, these conditions will be referred to as Hands On and Hands Off. Having these two conditions allows for a potentially better understanding of the role of a person's hands in locomotion and stability.

The test setup used for Zimmerman's treadmill walking trials can be seen in Fig .2.2.

Fig. 2.2. Test Setup for Treadmill Trials. (Image from Zimmerman, 2016)

Zimmerman conducted testing on 7 healthy adult subjects (N=7, 2 Female, 5 Male), with a mean age of 26.7 years (s.d. 4.8 years, range 22-36 years), mean height 179.3 cm (s.d. 8.5 cm), and mean mass 81.4kg (s.d. 20.7 kg) (Zimmerman, 2016.) For all trials, Zimmerman used a passive cart-like walker which can be seen in Fig. 1.1. The user wears a harness that connects to the cart via soft spring connections Fig. 2.3. Springs of different stiffnesses are swapped out throughout the trial.

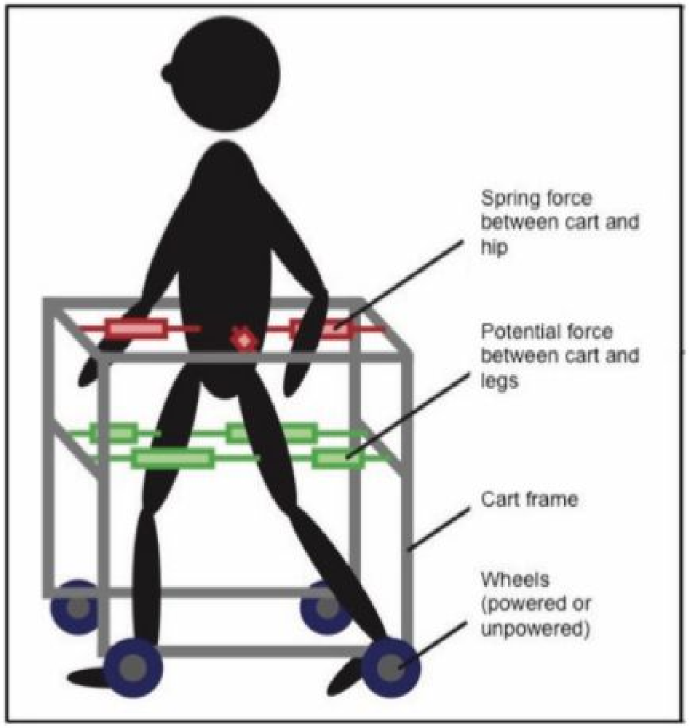


Fig. 2.3. Zimmerman's Walker-Like Exoskeleton Design Concept (Zimmerman, 2016). The cart is connected to the user via springs or potentially other sources of force.

The Oxycon Mobile metabolic measurement system seen in figure 2.2 allows for the user's oxygen and carbon dioxide flux to be recorded, which relates to the metabolic energy exerted while walking. Zimmerman used a Bertec split-belt treadmill with integrated load cells for her research. This allows for force measurements to be taken. For the quiet standing trials, standalone force plates were used to measure the GRFs of the user.

Vicon motion capture cameras are positioned around the treadmill to capture the motion of the subject and the cart (Fig. 2.1, 2.2). The motion is collected by placing reflective markers (**Fig 2.4.**) on the user which is then able to be picked up by the Vicon infrared cameras (**Fig. 2.1, 2.2**).

Fig. 2.4. Reflective Markers.

2.2 *Arduino Coding and Hardware for Active Version of Exoskeleton*

In this section, we describe some of our research and instrumentation to modify and improve Zimmerman's cart-like walker to being more controllable by the user, by the researcher, or by automatic control. The propulsion mechanism used in the active cart-like walker is a 350N hub motor that is centrally located in the rear of the cart (Fig. 1.1). The initial wiring of the hub motor and controller uses a throttle lever connected to a hall effect sensor that can sense changing voltage that is induced by a change in the throttle position (Fig. 2.5). The controller is then able to provide assistance proportional to the throttle signal voltage.

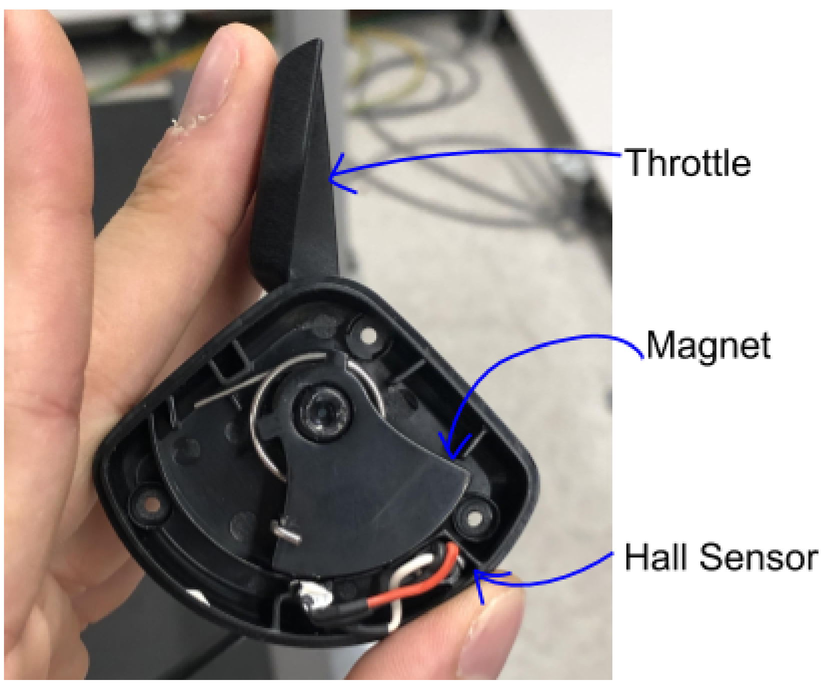


Fig. 2.5. Hub Motor Throttle Mechanism.

To have consistent testing methods, the throttle signal needed to be reproducible and selectable- i.e. The same assistance level can be applied across subjects and a specific assistance level can be selected by the user.

An Arduino Uno with an integrated WiFi and BLE shield was used to simulate a throttle signal that can be controlled wirelessly by the researcher, or self-selected by the user using an actuator on the cart. Fig. 2.6 shows our prototype, using which we performed a pilot overground walking test with one subject before human subject trials needed to be stopped.

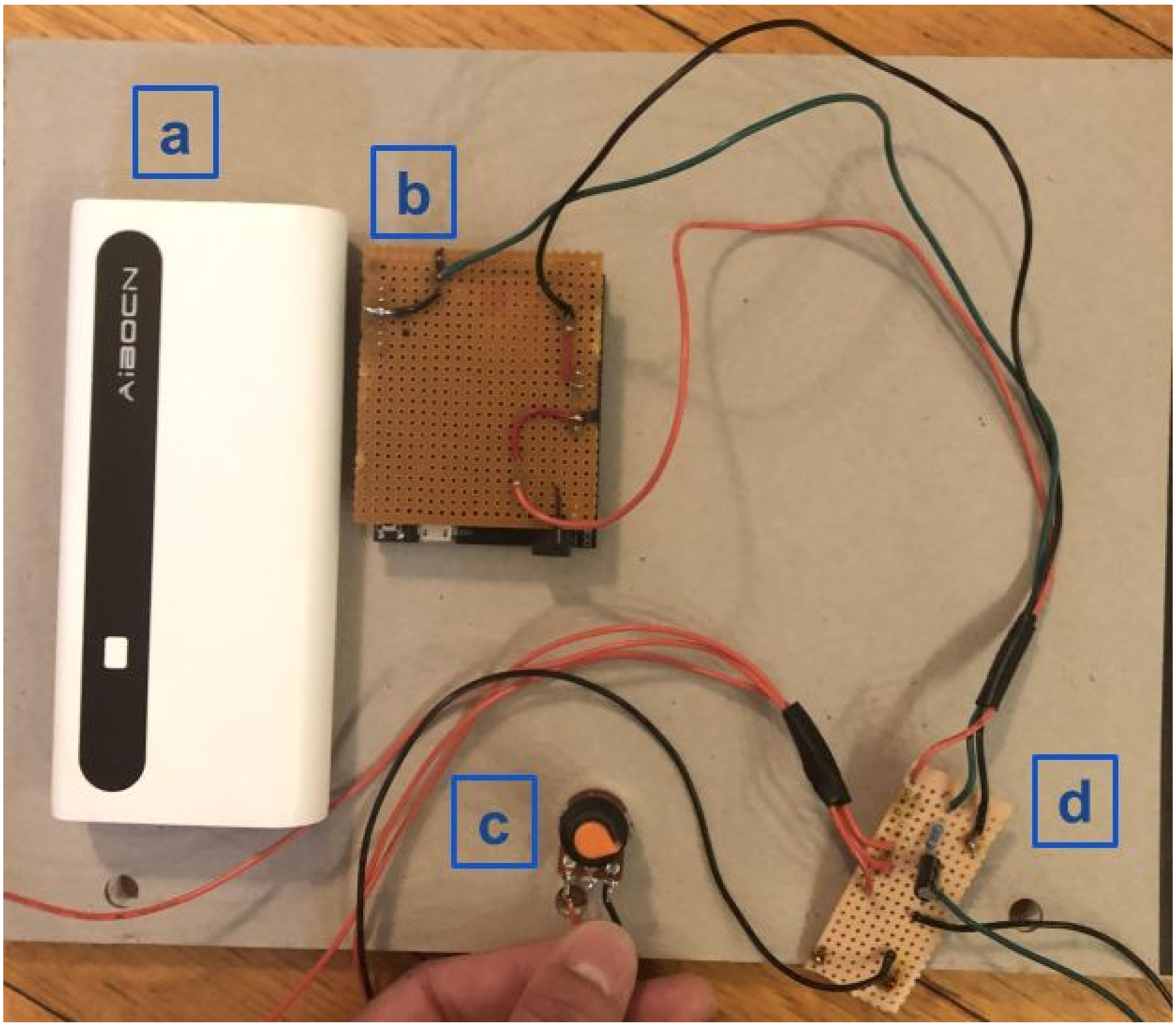


Fig. 2.6. Arduino Simulated Throttle Prototype. **a)** External Power Source, **b)** Arduino Uno 3 Wifi/BLE, **c)** Potentiometer, **d)** RC Filter.

The Arduino Uno is powered by an external 10000mAh with both a 5V/2.1A and 5V/1.0A USB output (Fig. 2.6 b,a). This allows for trials to be performed without wires, i.e. the user can walk with the cart unencumbered by any hardwired connections outside of the subject-device system. A 1 kOhm potentiometer is used as the control input method for trials where the user self-selects the most helpful assistance level (Fig. 2.6 c). The voltage level across the actuator terminals is read by the Arduino Uno which then responds with the corresponding assistance. This is achieved using the map() function in Arduino IDE which can be seen in the code in Appendix A1. For trials where the assistance level is controlled by the researcher, the throttle signal can be set through the serial monitor via WiFi or BLE throughout the trial. An RC filter with a 5.1 KOhm resistor and 10 μF was used to smooth out the pulse-width modulation output from the Arduino Uno (Fig. 2.6 d).

2.3. Planned Metabolic and Preferred Speed Trials

Our initial proposed research involved performing a few different types of human subject trials. First, once we achieved the ability to carefully provide a fixed assistance level with the cart, we planned to perform treadmill walking trials in which the subject walks at a few different constant assistance levels but at a fixed speed. Metabolic cost would be measured to determine the optimal assistance level at any given speed. Motion capture, and ground reactions would also be measured to understand how the metabolic cost is reduced, mechanistically. We also planned overground walking trials in which the preferred walking speed with the cart would be measured with different fixed assistance levels. Then, we could test if these preferred walking speeds are metabolically optimal based on our treadmill-based metabolic measurements at different speeds and assistance levels.

2.4 Analyses of Center of Pressure and Ground Reaction Forces

All new results produced in this thesis is purely computational and relies on the data produced from Zimmerman's research (Zimmerman, 2016.) MATLAB R2019a was used to generate plots of the individual left and right foot centers of pressure as well as the net center of pressure as a function of time and space. All centers of pressure and ground reaction force time series data were filtered first with a 5th order low pass Butterworth filter with a frequency cut-off of 40 Hz (Fig..

Correlation coefficients were found using the MATLAB command corrcoef() for the following items: left versus right foot center of pressure displacement in the anterior-posterior, and medial-lateral directions, and, anterior-posterior vs medial-lateral center of pressure displacement for each foot individually as well as the combined center of pressure. To assess whether these calculated correlation coefficients are positive or negative in a statistically significant manner, we performed one-sided t-tests using the MATLAB command *ttest*. This command outputs whether the null hypothesis is accepted or rejected (based on a 5% significance level) and the corresponding p value. In these tests, the null hypothesis is that the distribution that the quantity is drawn from has mean zero and the alternative hypothesis is that the quantity is systematically positive or negative (and we do a right-sided or left-sided test, respectively).

The displacements of the filtered center of pressure from the mean were also calculated and plotted for anterior-posterior and medial-lateral directions. All trials were plotted on a single figure for a given subject. This allows for any trends between the spring stiffness and the center of pressure displacement to be observed. Time series data was also plotted to observe any trends such as relative frequency of oscillation between anterior-posterior and medial-lateral direction as well as spot any deviations from the expected overall trends. Identical analyses were performed for GRFs.

Why analyze Centers of Pressure and Ground Reaction Forces? The dynamics of quiet standing is analogous to that of balancing a stick with your hand (an inverted pendulum on a cart). The "hand" is like the center of pressure and the inverted pendulum is the body. We move the hand in response to how the stick is falling and analogously, we move the overall CoP relative to CoM to control standing. Similarly, horizontal ground reaction forces are important to understand quiet standing as they are the restoring forces that keep the inverted pendulum from toppling. Here, by analyzing the individual leg contributions to the overall center of pressure and the horizontal force we characterize how the two legs share the function.

CHAPTER 3: Results

3.1 *Analysis of Standing Stability Using Center of Pressure*

In the rest of this chapter, we use the abbreviation AP for AP (fore-aft) and ML for medio-lateral (sideways). There are different ways of assessing standing stability, but one common practice is to analyze the center of pressure. The first useful piece of information is to look at the center of pressure as a function of time (**Fig. 3.1**). For standing trials, it shows the time-scale at which a subject sways, the overshoot the subject has as they maintain stability, and the responsiveness of the subject. We calculate and plot the correlation coefficients between a person's left foot center of pressure and right foot centers of pressure along each direction (**Figs. 3.2, 3.3**), the correlation coefficients between the AP and ML centers of pressure, both for each foot considered individually and for the overall center of pressure of both feet combined (**Figs. 3.4, 3.5**). The combined center of pressure of the two feet together is the weighted mean of the individual center center of pressure, weighted by the individual vertical forces. Next, we plot the AP and ML displacement of the center of pressure from the mean (**Fig. 3.6**). The standard deviations for all subjects and trials is also plotted to complement the AP/ML displacement of center of pressure (**Fig. 3.7**). This is useful for determining the effect that the spring stiffnesses have on a single subject.

3.1.1 *Background*

In this thesis, we only present an initial analysis and there is much potential to expand on this in further research. Even so, qualitative trends such as the relative time-scale with which a subject sways as well as the relative magnitude of oscillations of the center of pressure of an individual foot from the mean position can help to understand the motion of subjects as they sway.

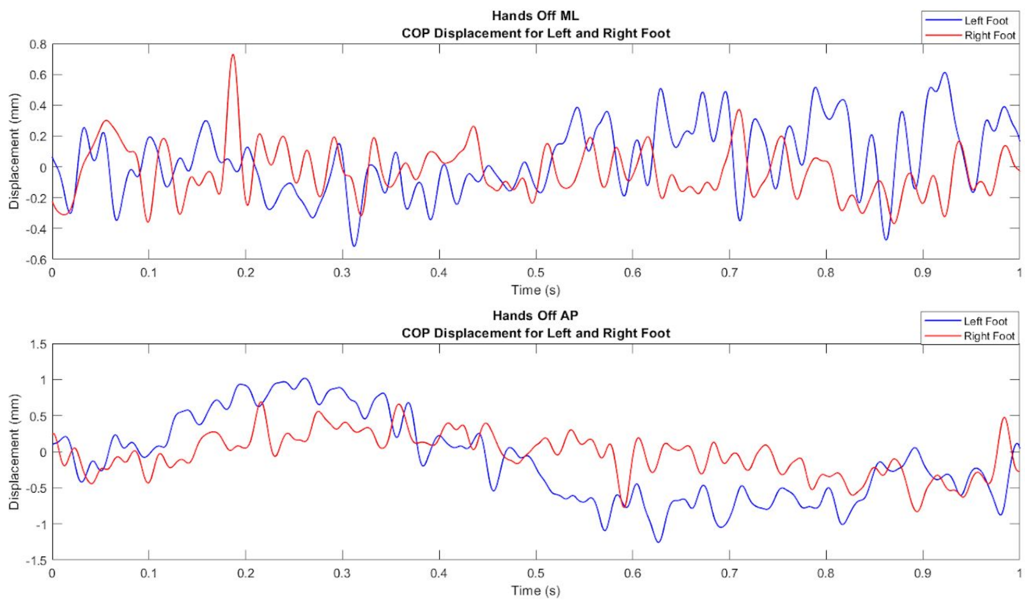


Fig. 3.1. Time-series data for one subject and specific trial in the AP and ML direction for one second. The processed signals of the left foot and right foot center of pressure displacement are plotted individually.

The center of pressure for the left and right foot were plotted separately in both the AP and ML directions with respect to time (Fig. 3.1) No specific trends are apparent in figure 3.1 that are also present in other subjects.

3.1.2 *Center of Pressure Correlation Coefficients*

Correlation coefficients were used to determine any relation between control with the left and the right foot, and any trends between AP and ML components of center of mass and ground reaction forces. Figure **3.2** shows a plot of the correlation coefficients between the left and right foot center of pressure displacement in the ML direction. The Hands On and Hands Off conditions are plotted on the same graph.

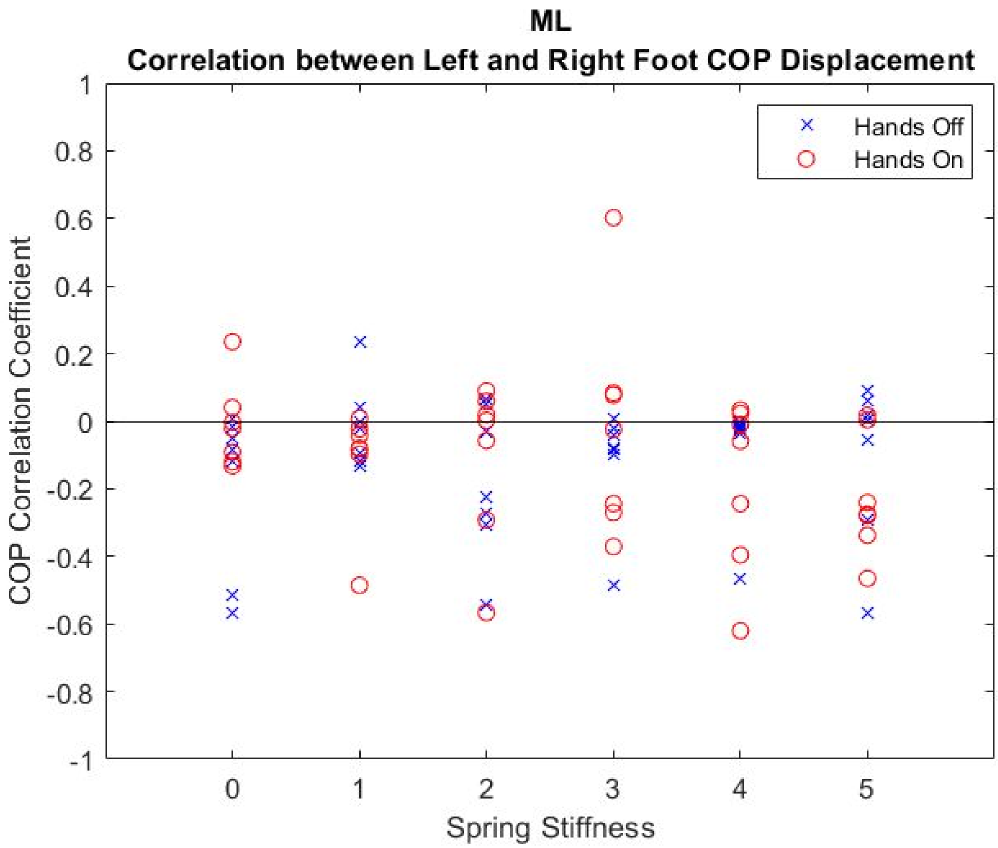


Fig. 3.2. The correlation coefficient between the left and right foot centers of pressure displacement in the ML direction is plotted for all subjects and trials. The Hands Off and Hands On conditions are distinguished by their markers.

There is a negative correlation between the left and right foot center of pressure in the ML direction. That is, the centers of pressure of the left and right feet typically move in opposite directions in the ML direction; if one moves to the right, the other moves to the left and vice versa. A t-test across all subjects and trials was performed and determined this negative correlation to be statistically significant (p-value < 0.001). No systematic trends are observed when comparing Hands On and Hands Off correlation coefficients.

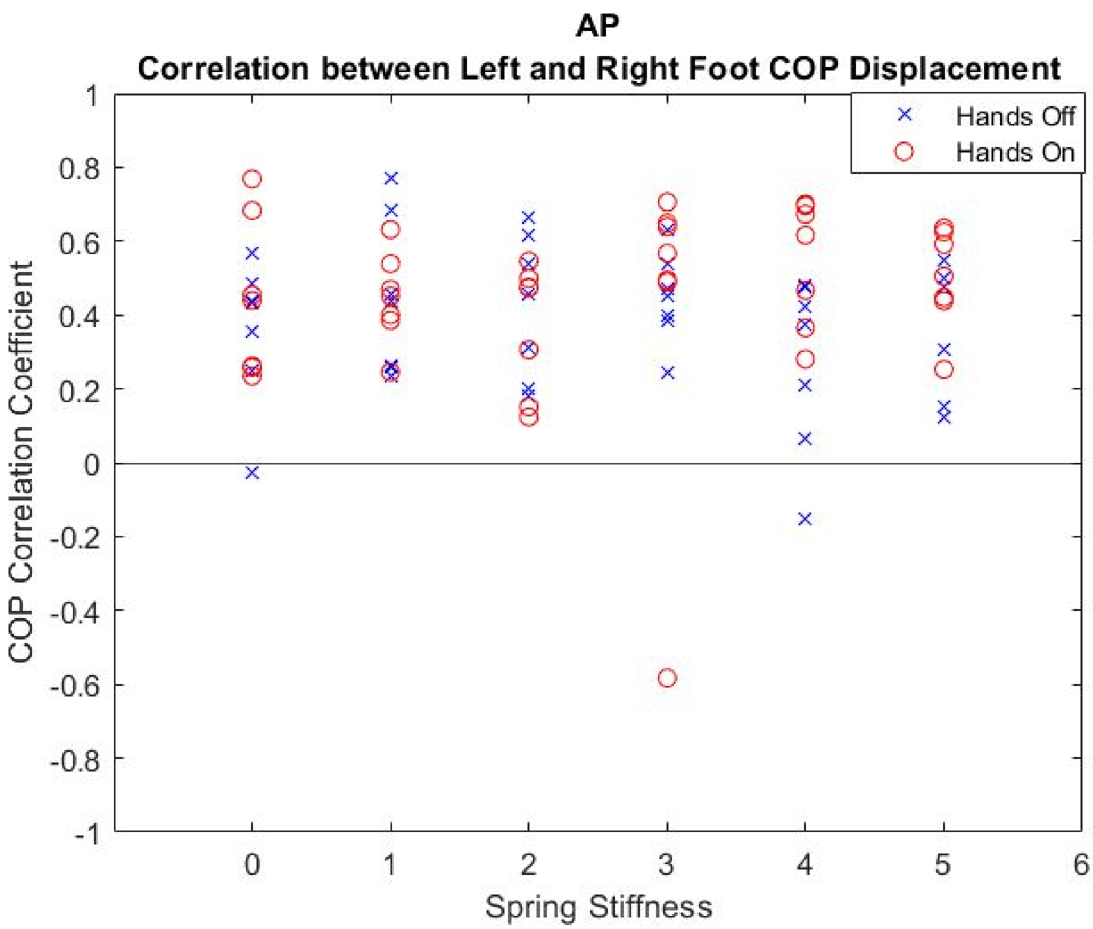


Fig. 3.3. The correlation coefficient between the left and right foot centers of pressure displacement in the AP direction is plotted for all subjects and trials. The Hands Off and Hands On conditions are distinguished by their markers.

The correlation between the left and right centers of pressure in the AP direction was computed (Fig. **3.3)**. The correlation coefficient between the left and right foot center of pressure displacement was found to be positive for most subjects and trials. A t-test determined p-values much less than 0.001 for the Hands On and Hands Off conditions making these observations statistically significant. As with the ML direction, there are no systematic trends between the Hands On and Hands Off condition correlation coefficients.

Correlation coefficients were also computed for the AP and ML components of the center of pressure displacement. These are depicted for each foot individually in figure **3.4** and for the combined center of pressure in figure **3.5**.

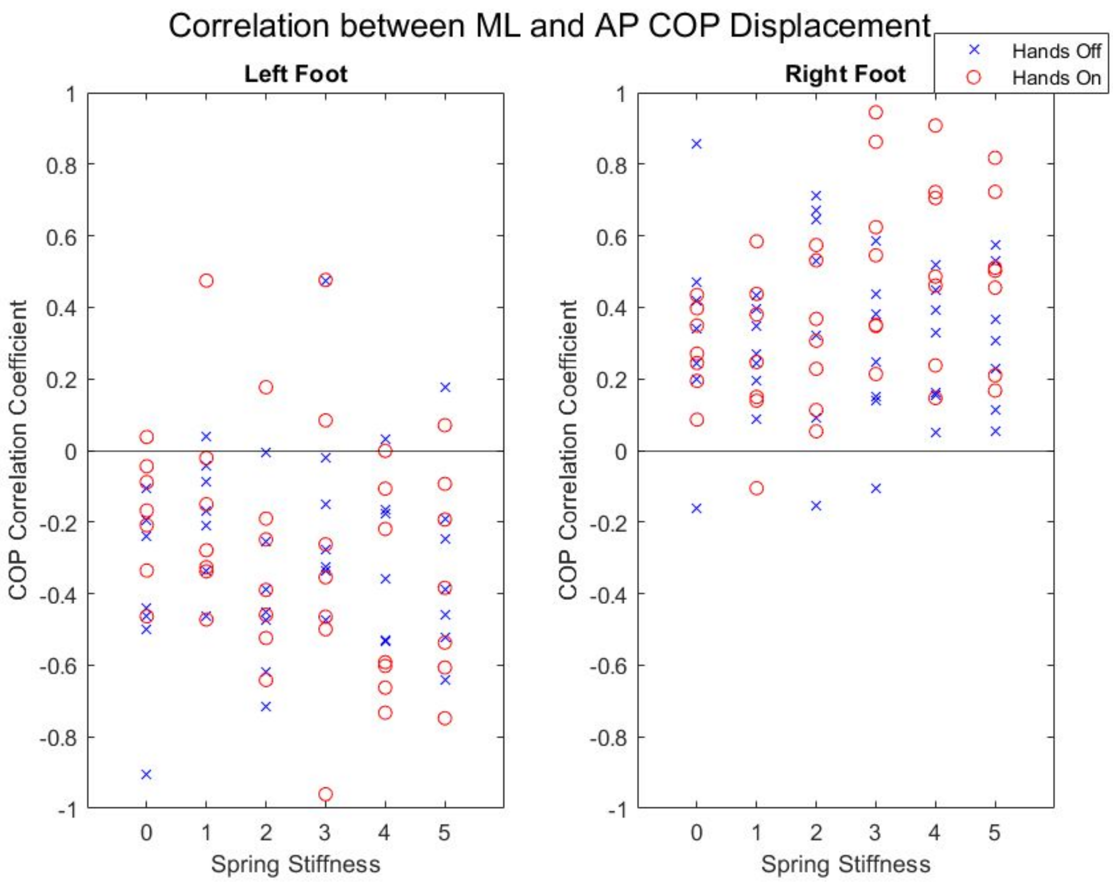


Fig. 3.4. Correlation between AP and ML center of pressure calculated for each individual foot. Hands On and Hands Off condition data were plotted together.

The plotted correlation coefficients reveal a negative correlation between the AP and ML centers of pressure for the left foot across all subjects and trials. Conversely, a positive correlation between the AP and ML centers of pressure is seen for the right foot. A t-test revealed p-values < 0.001 for all conditions and both feet. No observable trends can be seen between the Hands On and Hands Off condition data.

3.1.3 *Understanding AP-ML CoP Correlations*

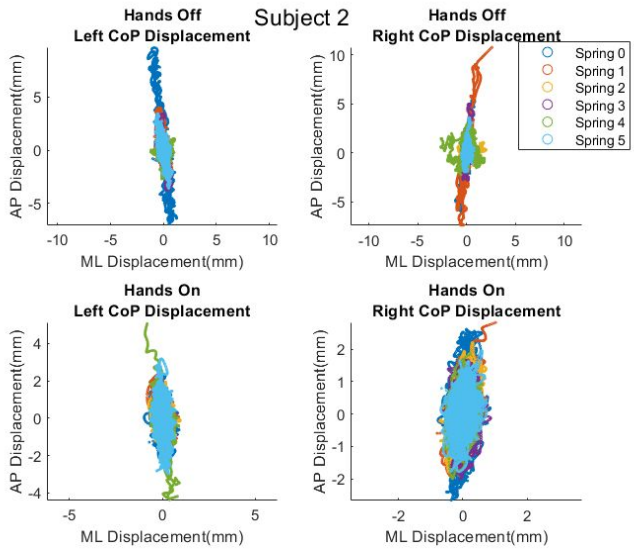


Fig. 3.5. The ML and AP displacements of the center of pressure for all trials for a single subject is plotted. The top two plots are for the Hands Off condition and the bottom two plots are for the Hands On condition. The left and right foot displacements are distinguished in separate plots and aligned left and right respectively.

The filtered displacement of the center of pressure in the AP and ML direction was plotted to possibly give insight into how each individual subject moves throughout the standing trial. In Figure **3.5** such plots are shown for one subject. Although the magnitude of the displacements is subject specific, there is a general trend that can be observed. The AP and ML centers of pressure of most subjects move such that the left center of pressure moves along a line with negative slope and the right CoP moves along a line with positive slope. This trend also explains the negative and positive correlations for the left in right foot seen in figure 3.4. This trend may be due to a number of things; the foot positioning of the subject, the alignment of the subject relative to the individual force plate coordinate systems, or some other systematic error. Further research would need to be done to determine whether these trends are significant.

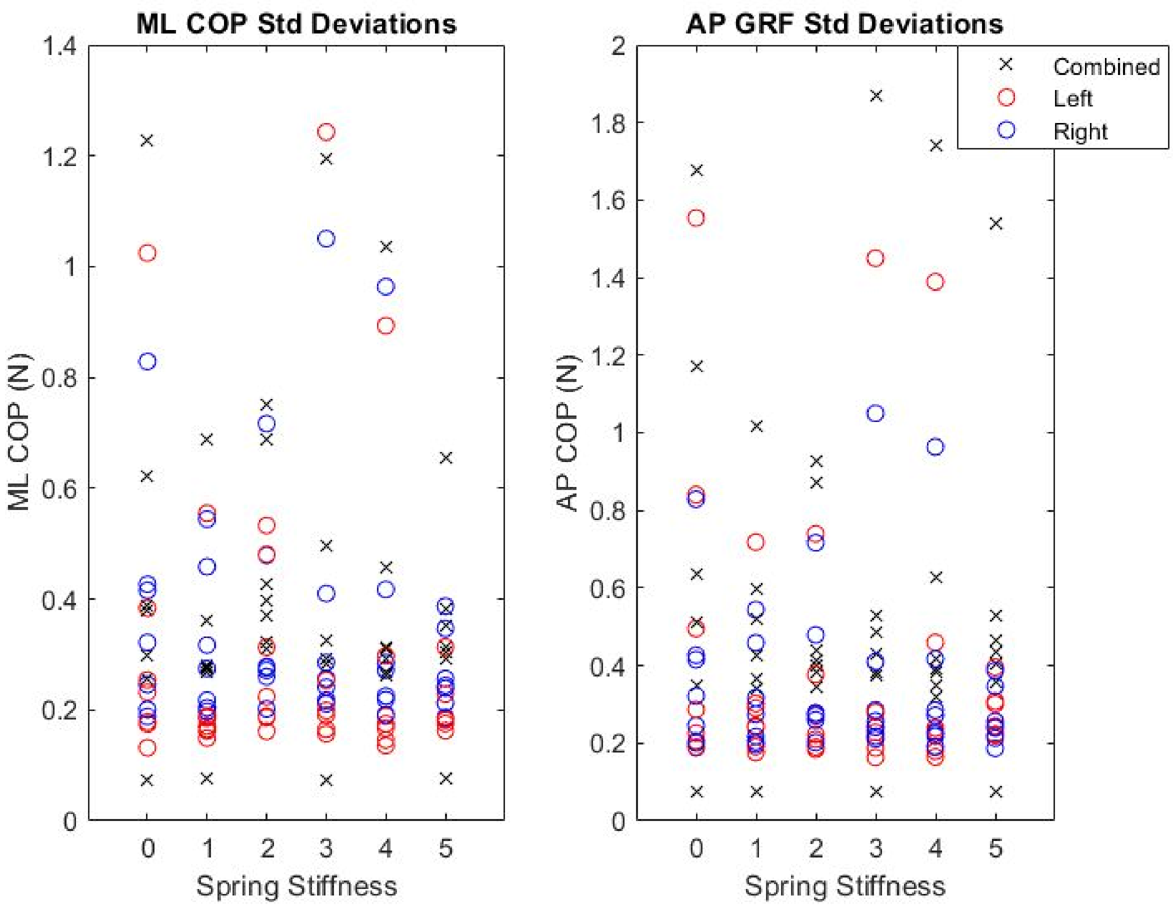


Fig. 3.6. Standard Deviations of ML and AP centers of pressure across all subjects and trials.

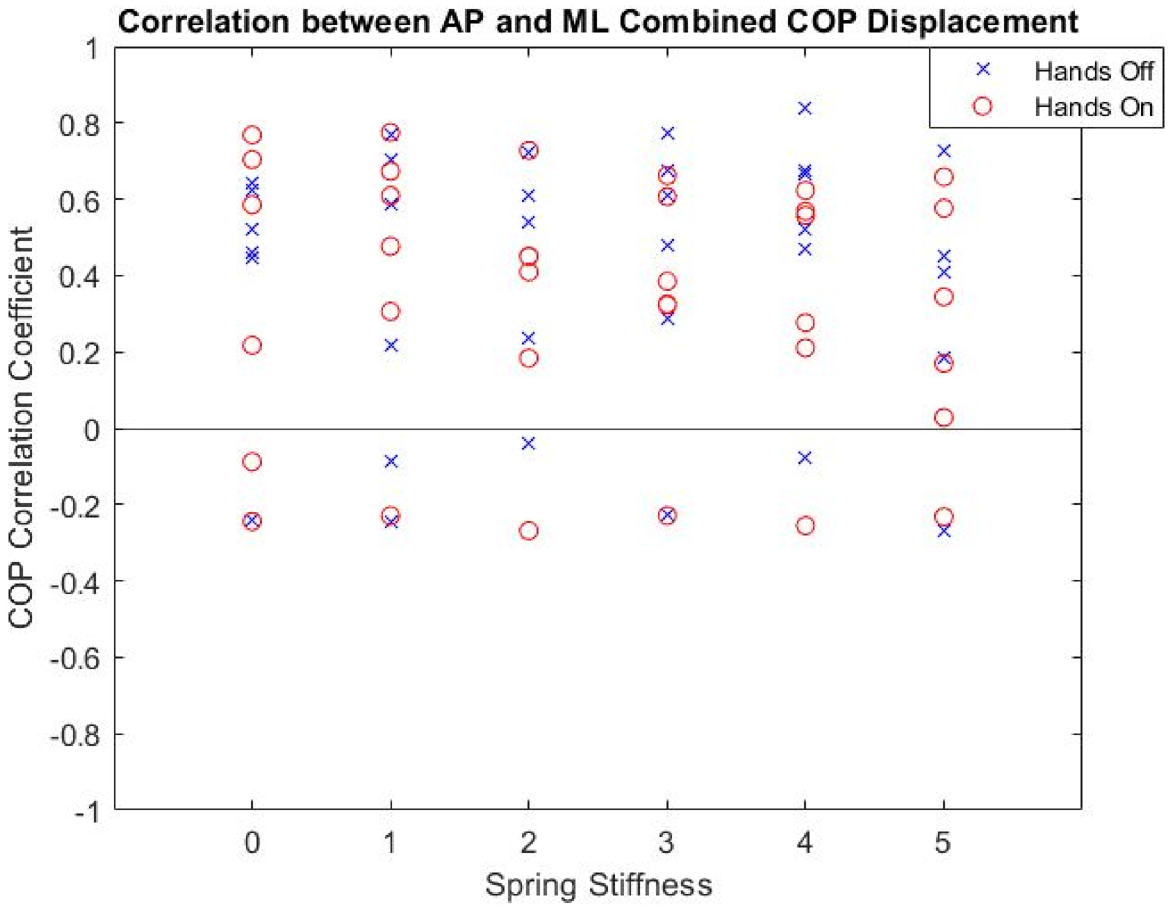


Fig. 3.7. Correlation between the combined AP and combined ML center of pressure displacement. Hands On and Hands Off data were plotted on the same figure.

As seen in figure **3.7**, there is an overall positive correlation between the combined AP and combined ML and are considered statistically significant ($p<0.001$). There is one subject (subject 4) who had negative correlations for nearly every trial.

3.2 *Ground Reaction Force Analyses*

Ground reaction forces can be analyzed in the same manner as the center of pressures which will provide a clearer understanding of the interplay of the two quantities during quiet standing. Figures **3.8** and **3.9** show plots of the ML and AP forces with time for a selected subject. Figures **3.10** and **3.11** show the correlation coefficient between the left and right foot in the ML and AP direction respectively. Figure **3.12** shows the correlation coefficient between the ML and AP center of pressure displacements for the left and right foot individually. The same analyses were done for combined center of pressure and the results are shown in figure **3.13**. Complementary to these plots are the plots of the AP and ML ground reaction force components versus time (figure **3.14)**.

3.2.1 *Background*

Visualizing the force data as a function of time is useful for understanding how subjects modulate their weight distribution throughout a trial. An initial analysis of these time series will be conducted in this paper, but further research needs to be done to fully understand the ground reaction forces like those shown in figure 3.7.

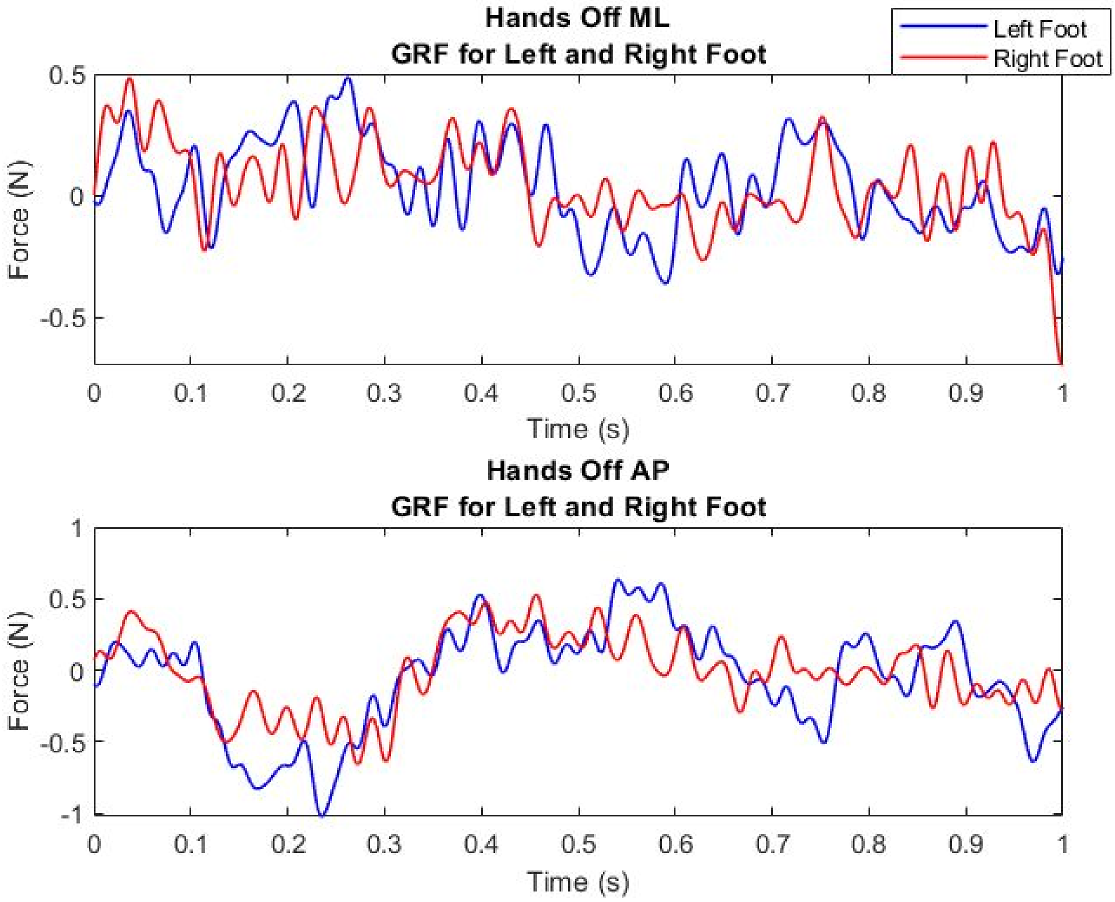


Fig. 3.8. A one second window of the force in the ML and AP directions for the left and right foot individually.

3.2.2. *Ground Reaction Force Correlation Coefficient*

Figure **3.9** shows a positive correlation between the left foot and right foot force in the ML direction. A positive correlation between the AP ground reaction force of the left and right foot was also found (Fig. 3.9).

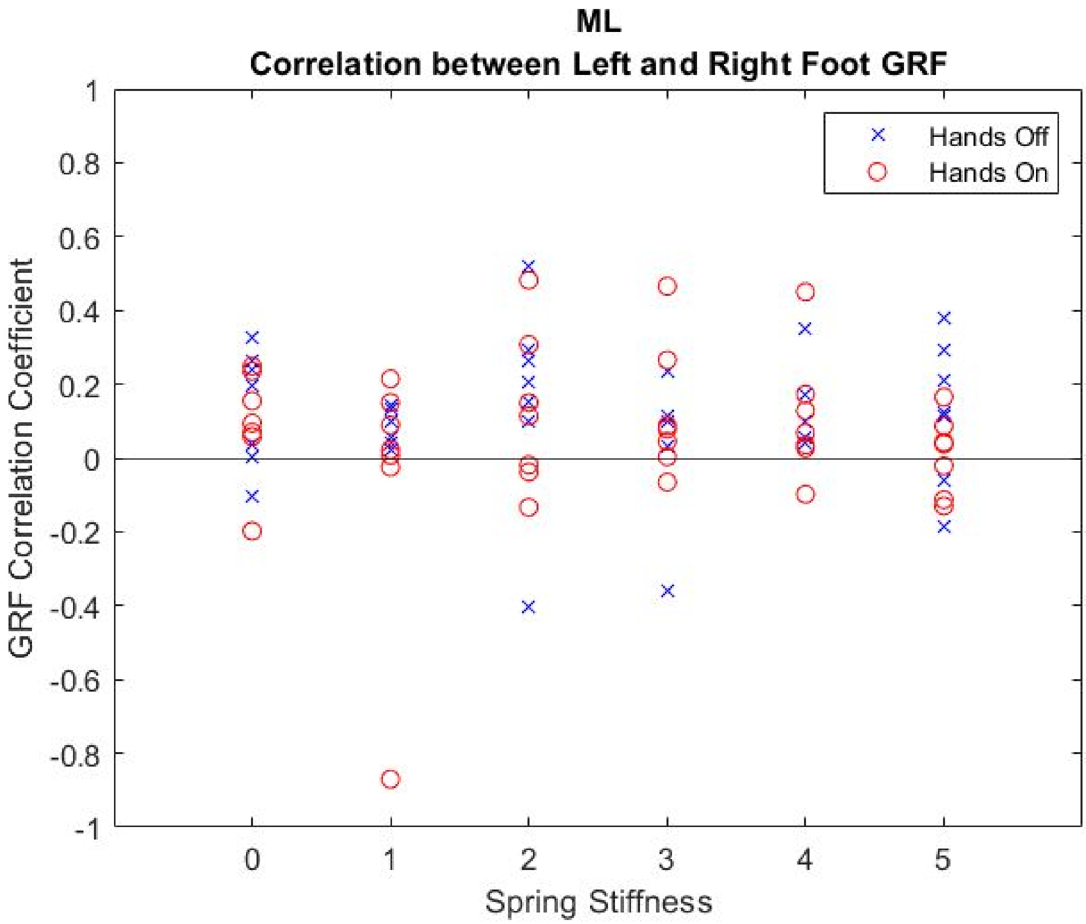


Fig. 3.9. The correlation coefficients of the left and right foot force in the ML direction. Both the Hands On and Hands Off condition data were plotted.

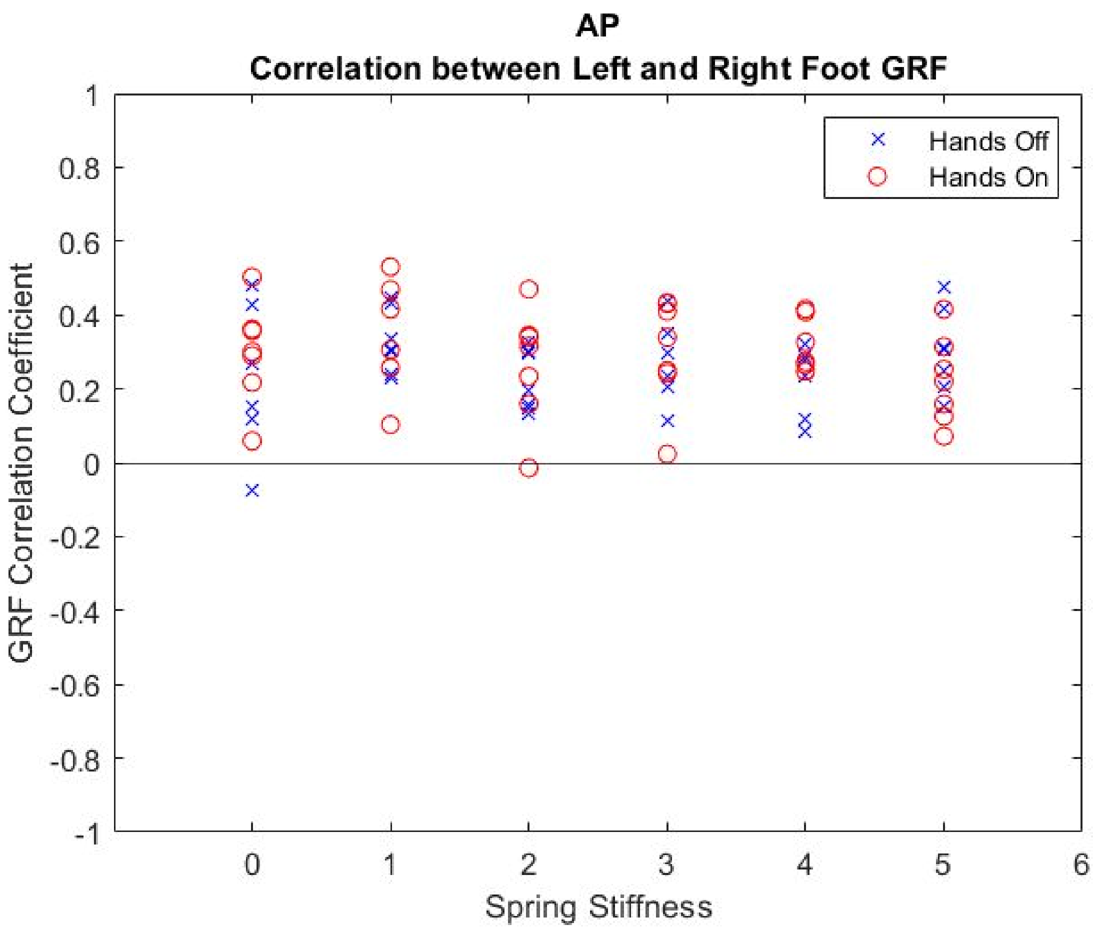


Fig. 3.10. The correlation coefficients between left foot and right foot force modulation in the AP direction. Both Hands On and Hands Off condition data was plotted.

A t-test was performed for the correlation coefficients found for the Hands On and Hands Off conditions separately. It was determined that this positive correlation is statistically significant for the Hands Off and Hands On condition ($p < 0.05$). Both conditions are statistically significant for correlation coefficients found for the AP direction (p-value < 0.001). Recalling that these horizontal forces are the "restoring forces", the positive correlations mean that the left and the right legs usually work together to produce a restoring force in any direction.

No noticeable trends can be observed between the ML and anterior-poster force for the left and right foot individually (**Fig. 3.11**). This was confirmed by a ttest which gave p-values much larger than 0.1.

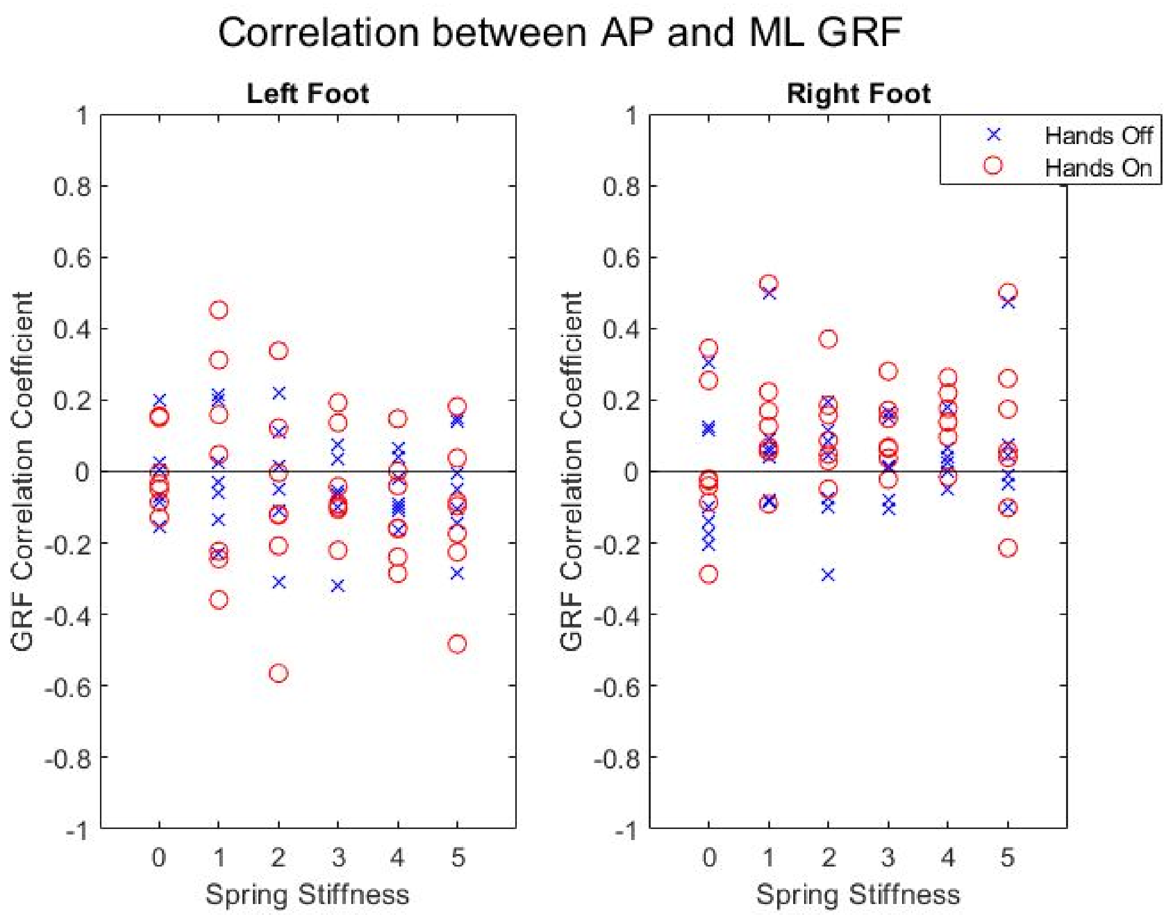


Fig. 3.11. The correlation coefficients between the AP and ML GRF modulation for each foot individually. Both Hands On and Hands Off condition data points were plotted.

Figure 3.12 shows the ML and AP ground reaction forces. There are no noticeable changes in the magnitudes of the ML and AP forces for varying spring stiffnesses. This corroborates with the results shown in figure 3.11. The fact that the distribution of the AP and ML forces don't have any significant directionality means that the deviations they oppose do not have any directionality either.

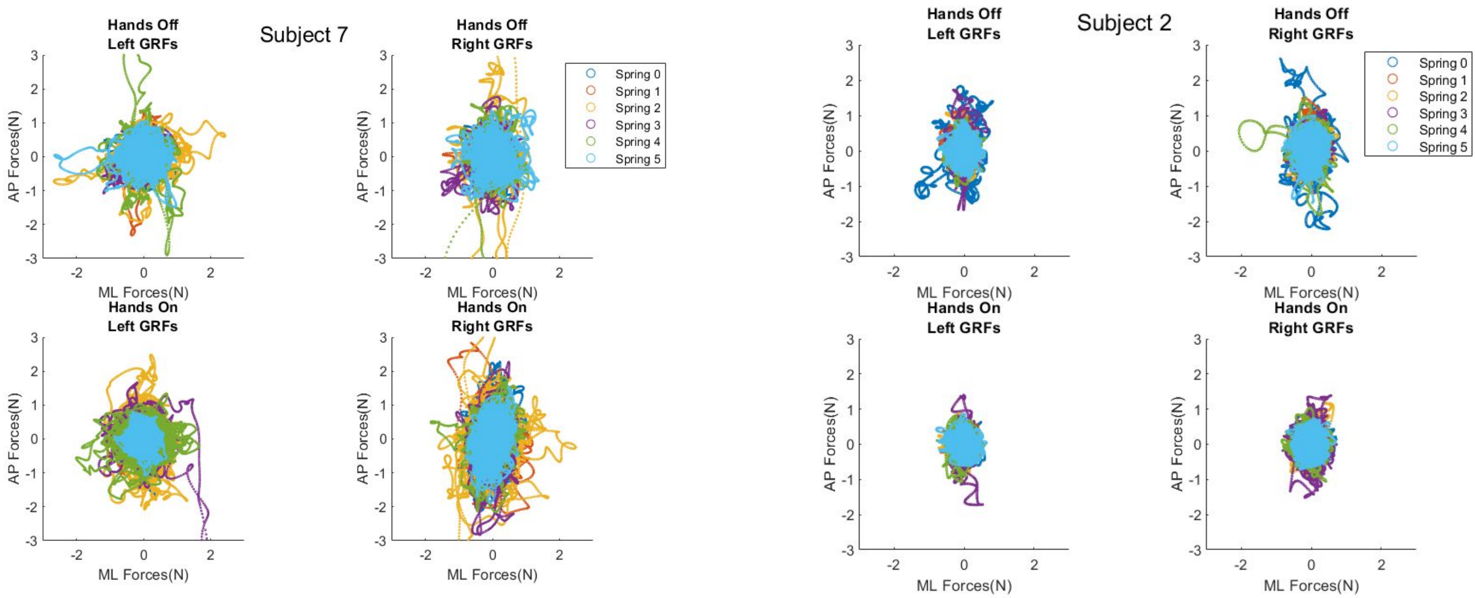


Fig. 3.12. Variation of the GRF components in the AP and ML direction from the mean. Two sample subjects are shown above. For the Hands On and Hands Off conditions on separate plots.

The standard deviations of the left and right ground reaction forces and the combined ground reaction forces was also calculated (Fig. 3.13). No discernible trends were noticed for neither the ML ground reaction force nor the AP ground reaction force for varying spring stiffness. To be fair, we should compare the cases with springs with the HandsOff case with Spring 0 (no spring) and that will be done in a future iteration of this work.

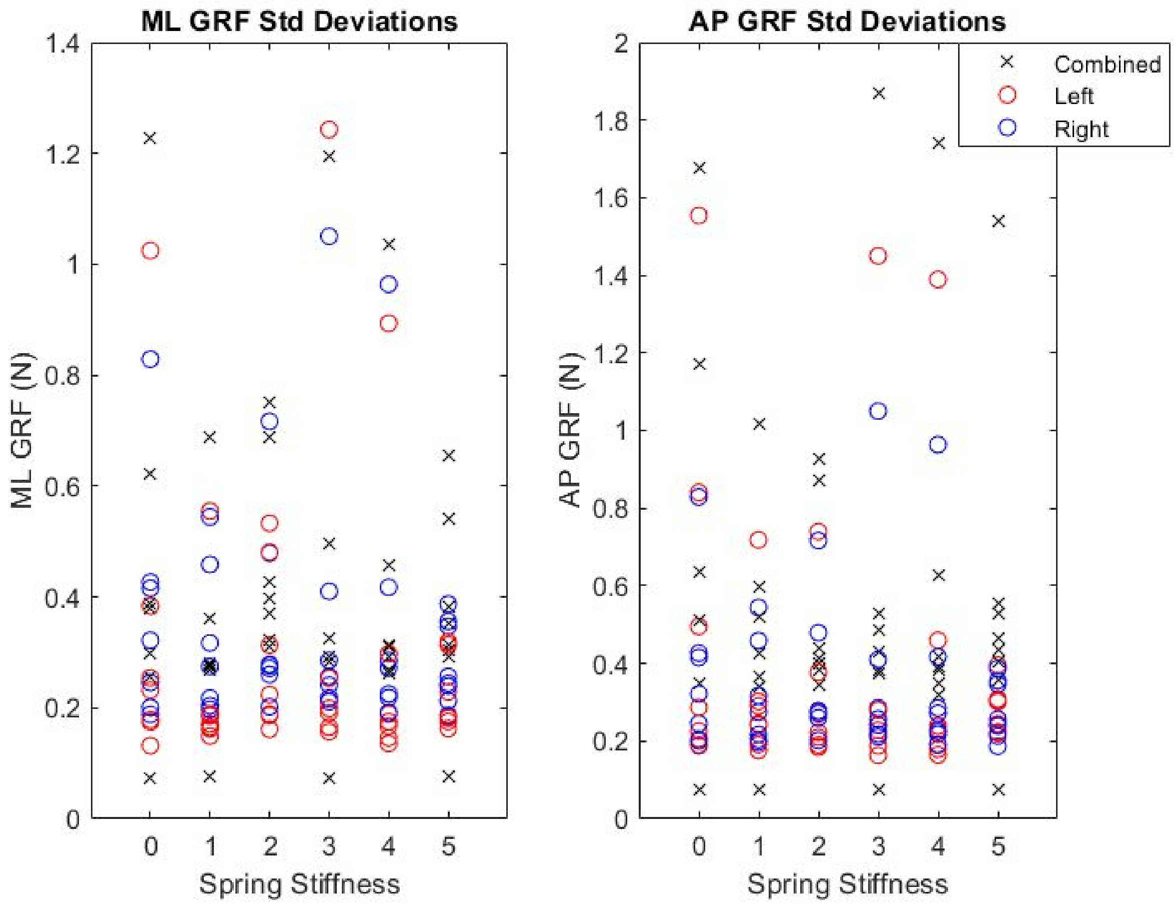


Fig. 3.13. Standard deviation of ML and AP ground reaction forces across all subjects and trials.

There are no observable trends with the combined correlation coefficients for the ML and AP ground reaction forces (Fig. 3.14). This is confirmed with the t-test which deemed any positive or negative trends to be statistically insignificant.

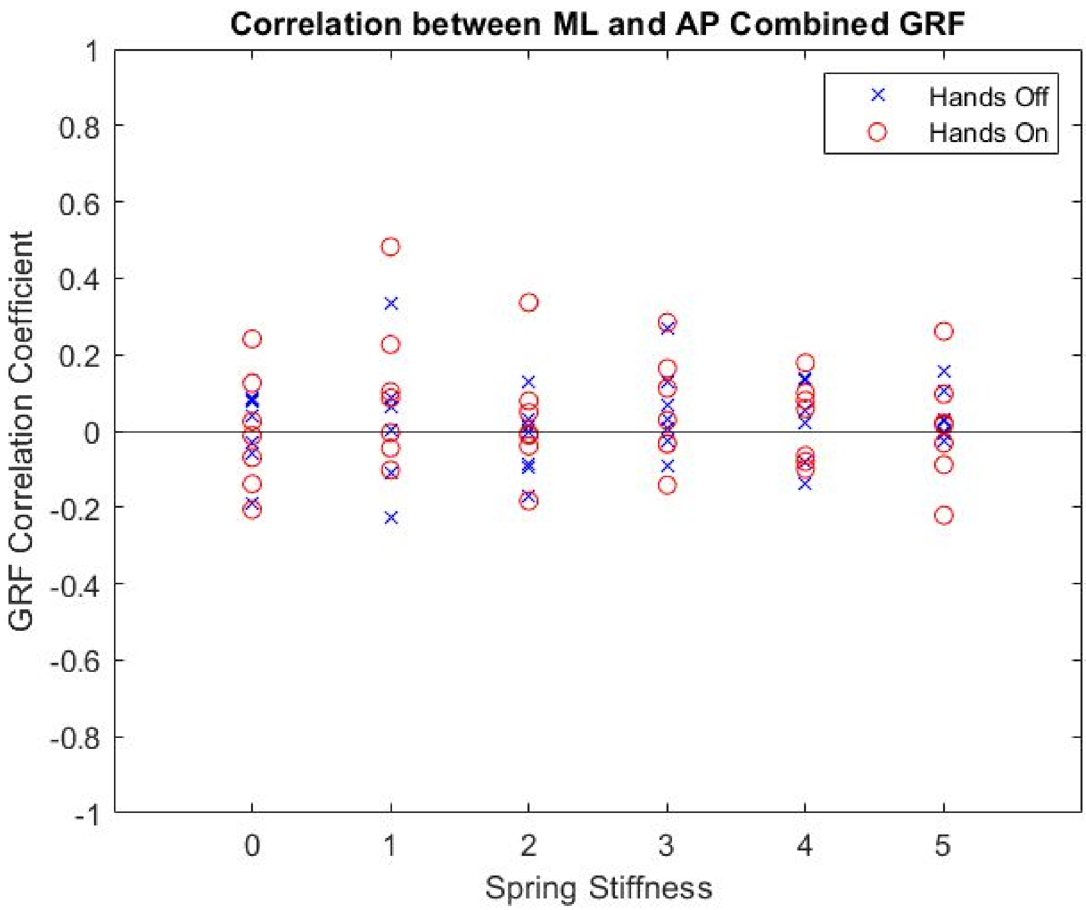


Fig. 3.14. The correlation coefficients between the AP and ML GRF modulation for the combined forces. Both Hands On and Hands Off condition data points were plotted.

3.3 *Findings from Generated Plots*

There is a negative correlation between the left and right foot center of pressure in the ML direction. The correlation coefficient between the left and right foot center of pressure displacement was found to be positive for most subjects and trials in the AP direction. The plotted correlation coefficients reveal a negative correlation between the AP and ML centers of pressure for the left foot across all subjects and trials. Conversely, a positive correlation between the AP and ML centers of pressure is seen for the right foot. The AP and ML centers of pressure of most subjects move such that the left center of pressure moves along a line with negative slope and the right center of pressure moves along a line with positive slope. There is an overall positive correlation between the combined AP and combined ML and are considered statistically significant ($p<0.001$).

There is a positive correlation between the left foot and right foot force in the ML direction for the Hands On condition and in the AP direction for both the Hands On and Hands Off condition. No noticeable trends can be observed between the ML and anterior-poster force for the left and right foot individually. There are no noticeable changes in the magnitudes of the ML and AP forces for varying spring stiffnesses. No discernible trends were noticed for neither the ML ground reaction force nor the AP ground reaction force for varying spring stiffness. There are no observable trends with the combined correlation coefficients for the ML and AP ground reaction forces.

CHAPTER 4: Discussion

4.1 ***Correlation Coefficients***

Two main types of correlation coefficient analyses were performed. One was for studying the correlation between the left and right foot centers of pressure and GRFs. The second studied the correlation between the ML and AP components of center of pressure and GRFs for the left and right foot individually as well as the combined left and right foot.

4.1.1 ***Left Foot vs Right Foot***

From performing correlation coefficient analyses on the center of pressure data, it was determined that the left and right foot positions from the mean are positively correlated in the anterior-posterior directions and negatively correlated in the medial-lateral direction. This makes sense when imagining a subject rocking back and forth and side-to-side while trying to maintain stability. If the person has feet even splayed outward while standing ("duck feet"), the center of pressure may move along the feet producing the observed correlations. These general trends can be observed in the center of pressure displacement in Fig. 3.5. For the majority of subjects, the center of pressure displacement throughout the trial follows a slanted trajectory. This means as a subject's center of pressure moves toward the anterior direction, the medial-lateral components move laterally from the mean. Likewise, as the center of pressure moves toward the posterior direction, medial-lateral components move medially. This combined with how direction is defined causes negative medial-lateral displacements for the left foot and positive medial-lateral displacements for the right foot when the center of pressure is moving in the anterior direction and vice versa. Because the movement of center of pressure in the medial-lateral direction is opposite for the left and right foot, the negative correlation coefficient that was calculated makes sense.

Similarly, the correlation coefficient analyses of the ground reaction forces revealed a positive correlation in the medial-lateral direction and in the anterior-posterior direction for both the Hands On and Hands Off condition. Recalling that these horizontal forces are the "restoring forces", the positive correlations mean that the left and the right legs usually work together to produce a restoring force in any direction. That is, given that there are potentially infinitely many ways to share the load between the two legs, the two legs share the load with a particular correlation. We would require a dynamical model with perhaps an inference of the underlying feedback controller and noise distribution to mechanistically explain thee level of the observed correlation.

4.1.2. ***Medial-Lateral vs Anterior-Posterior***

There is a negative correlation between the medial-lateral and anterior-posterior center of pressure displacements for the left foot (Fig. 3.4) Conversely, there is a positive correlation between the medial-lateral and anterior-posterior center of pressure displacements for the right foot (Fig. 3.4). One explanation for these correlations is by again imagining a subject rocking back and forth and side-to-side while trying to maintain stability, with slightly outwardly splayed feet. As a subject rocks forward or backward, the anterior-posterior centers of pressure and ground reaction forces on both feet move in the same general direction. There are some physiological factors that may need to be considered such as the topology profile of the bottom of each subjects feet and/or their stances during quiet standing. No trends were observed for the combined ground reaction forces between the medial-lateral and anterior-posterior direction (Fig. 11-14).

4.2. *Implications for Future Work*

Future work on either the passive or active version of Zimmerman's cart-like walker should consider the results found in this paper. The studies of the centers of pressure and ground reaction forces during quiet standing did not reveal anomalous behavior. This substantiates the possibility for using such a walker without introducing enumberances to the user. Additionally, the calculated correlation coefficients revealed some synchronization of left and right foot centers of pressure and ground reaction forces in the anterior-posterior. This is perhaps expected, but is useful to know when considering future designs and analyses of Zimmerman's exoskeleton concept. A positive correlation between the medial-lateral and anterior-posterior center of pressure was found and a negative correlation for the left foot. This is further supported by the negative correlation found between the left and right foot displacement of center of pressure in the medial-lateral direction. This implies that there could be a systematic reason for this prescribed center of pressure trajectory. Performing quiet standing trials with motion capture data may provide further insight into these trends.

Perhaps the best way to understand the underlying mechanisms by which stability is achieved (and also explain the observed correlations) is to perform a mechanics-based "system identification" to characterize the feedback controllers involved. In ongoing work, we integrated the accelerations obtained from ground reaction forces to get the center of mass velocity and position. Then, we regress the ground reaction forces and centers of pressure against a delayed version of the center of mass state to obtain a simple proportional-derivative controller for human standing. The plan is to then understand human standing better by examining the properties of this feedback controlled dynamic system. Of course, we can consider more complex models too and feedback control at the level of each joint and joint torque.

4.3. *Limitations of Work*

The stability analyses performed in this paper provide a first glance at the stability of Zimmerman's cart-like walker during quiet standing. One major limitation to these analyses, was that they did not account for the kinetics and physiology of the subjects. Vicon motion capture data was not collected during Zimmerman's quiet standing trials which limits analysis to the standalone force plate measurements. The stability analyses performed are also only valid for cases of quiet standing. Analyzing data from Zimmerman's treadmill trials would give better insight into the stability of the user during gait and also has the additional insight given by the Vicon motion capture data. The analyses in this paper are also limited to healthy subjects and are not necessarily indicative of the results that would be seen in a user who has a movement disorder or physical disability.

CHAPTER 5: Conclusion and Future Work

5.1 *Summary*

This research focuses on the stability of a person using Zimmerman's passive cart-like walker. Analyses of both center of pressure displacements and ground reaction forces in the medial-lateral and anterior-posterior direction were performed. We computed correlation coefficients between the two comparative data sets and used a t-test to determine the significance of any observable correlations. It was thus determined that there is a positive correlation between the left and right components of: center of pressure in the anterior-posterior direction, and ground reaction forces in the medial-lateral and anterior-posterior direction. The left and right foot medial-lateral center of pressure displacements are negatively correlated. Additionally, the correlation between medial-lateral and anterior-posterior center of pressure displacement is negative for the left foot and positive for the right foot. The combined center of pressure displacement in the medial-lateral and anterior-posterior direction is positively correlated. There are also no observable differences between the Hands On and Hands Off centers of pressure and ground reaction forces.

5.2 *Recommendations for Future Work*

Further analysis needs to be conducted to assess the stability of Zimmerman's cart-like walker for all conditions of use. The following is recommended for further work on this topic:

- A more detailed statistical analysis of the center of pressure, center of mass, and ground reaction forces that looks at the relative phases, the overshoot in the center of pressure and ground reaction forces, as well as the settling time.

- Use linear or nonlinear regression to determine feedback controllers relating the leg forces and centers of pressure to the center of mass state. Then, a better PID controller can be programmed for the active version of Zimmerman's cart-like walker to improve stability further.
- Analyze the force plate and motion capture data for Zimmerman's treadmill trials for better insight into the stability of the user during walking.
- Integrate a differential drive to the two powered wheels to enable power turning (Zimmerman, 2016).
- Execute the original plan of this thesis to perform overground and treadmill walking trials with the active version of the cart with controlled assistance.

APPENDIX

A.1: Signal Processing

```
%% Filter Data

% % Smooth out signal with filter, cutoff frequency of ~40 Hz

fc=40;%cutoff frequency(Hz)
fs=1000;%sampling frequency
delta_t = 1/fs;

[b,a] = butter(5,fc/(fs/2),'low');

% FilteredCOPDisplacementAssignment();

load FilteredStanding.mat;
```

Fig. A1.1 A fifth-order Butterworth filter used for processing the Vicon data.

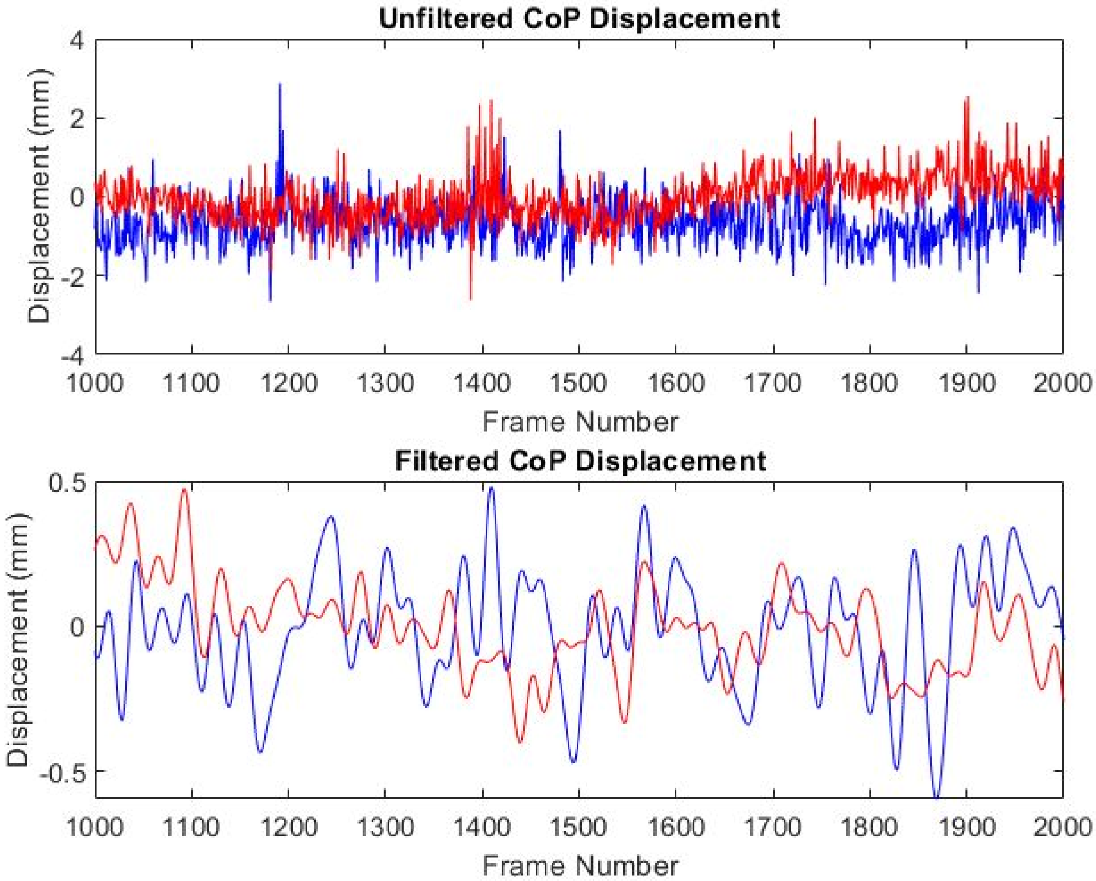


Fig. A1.2. Sample Figure of Effect of Filtering.

A.2: Arduino Throttle Simulator Code

```
[code]
//March 8, 2020

//include BLE library
#include "BluetoothSerial.h"
BluetoothSerial SerialBT;

//Declare constant variables

int const Throttle = 25;            //Throttle voltage signal outputted
through pin 25
int const Pot = 16;                 //Potentiometer postion read through
pin 16

//Declare changing variables

int Pot_current;                    //Stores current position of
potentiometer
int Pot_last = 0;                   //Stores last position of potentiometer
int Accel;                          //Stores accelerometer data
float Level;                        //Stores throttle level; derived from
Pot_position


void setup () {

  Serial.begin(9600);

  //Declare pinmodes
  pinMode(Throttle, OUTPUT);
  pinMode(Pot, INPUT);

  //Connect Arduino to computer via BLE
  SerialBT.begin("ESP32test");
  delay(1000);

}

void loop() {
```

```
  //Look for incoming data
  String inputFromOtherSide;
  if (SerialBT.available()) {
      inputFromOtherSide = SerialBT.readString();
      SerialBT.println("You had entered: ");
      SerialBT.println(inputFromOtherSide);
  }

Variable_Assistance();


}


void Variable_Assistance() {
  //Read pot position
  Pot_current = analogRead(Pot);
  Serial.println(Pot_current);

  //Map potentiometer resistances to voltages and set equal to variable,
"Level"
  Level = map(Pot_current, 0, 1000, 1.2, 4);
  Serial.println(Level);
}
[/code]
```

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